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Effects of Impulsive Interference upon A-M Voice Communication*

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The degree to which noise impairs the intelligibility of speech depends upon the characteristics of the noise. In this paper, which is concerned with electrical interference and radio communication, the questions are: (1) "what characteristics of the noise determine the degree of impairment," and (2) "what are the functional relations between intelligibility and the important characteristics of the noise?" Answers to these questions were obtained with the aid of articulation tests, conducted with a typical amplitude-modulation system and with a variety of electrical interferences.

INTRODUCTION

DURING the war, the problem of electrical interference in radio communication became more serious by the month. Radars, IFF's, electronic altimeters, pulse navigation systems, aircraft precipitation static, and jammers added their voices to the discordant chorus which, before the war, had been created largely by electrical machinery, ignition systems, diathermy apparatus, and atmospherics. Interference reduction programs were set up. Maximum noise specifications were written. The basic question arose: "How much interference can be tolerated?"

This question was short, but it was not simple. Even its statement in relative terms—how high a ratio of noise to signal can be tolerated—did not make it easy to answer. There were too many types of modulation, too many kinds of interference, and too many levels of tolerance.

The question did not receive an entirely satisfactory answer. Nevertheless, the asking served to point out how little was known, even for the simplest radio systems, about the relation between the intelligibility of speech heard over a radio link and the carrier-to-interference ratio. This paper is concerned with that relation as it obtains for a typical amplitude-modulation system operating in the presence of impulsive interference. It is concerned, further, with the way in which the relation between intelligibility and the carrier-to-interference ratio depends upon several non-intensitive characteristics of the interference.

DIMENSIONS OF IMPULSE INTERFERENCE

Impulse noise is defined as noise arising from disturbances which are essentially instantaneous. Thus interference from ignition systems and from electrical machines with sparking contacts is impulsive. The trains of pulses generated by the modulators of radars and certain other pulse-transmission systems also are included within the definition; the durations of the pulses are very short relative to the durations of the audio-frequency waves which they cause in the output circuits of radio receivers. Atmospheric static and aircraft precipitation static are also to some degree impulsive, and even fluctuation noise ("white" noise) may be thought of as an extremely dense concentration of extremely short pulses, occurring in random sequence.

Samples of impulse noise may differ from one another in a number of ways. First, there are samples in which the pulses are all alike and essentially rectangular in shape, following one another in regular succession. In such samples, the possible dimensions of variation include pulse amplitude, pulse duration, pulse repetition frequency (p.r.f.), and a number of other characteristics which are fixed if the amplitude, duration, and repetition frequency of the pulses are specified.[1] There are other samples of impulse noise in which the individual pulses are *not* all alike, or in which they are *not* essentially rectangular in shape, or in which they do *not* occur in regular succession. Innumerable patterns of this type are of course possible. Fortunately, however, by no means all of the possible patterns are encountered as interference with radio communication.

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[1] S. S. Stevens, J. Miller, and I. Truscott, J. Acous. Soc. Am. 18, 418 (1946).

The first step in working with radio interference is to set up a system of specification which takes into account the modes of variation just enumerated. The dimensions of such a system fall into two broad classes, intensitive and temporal. Since the selection of the particular intensitive and temporal attributes to be used in specifying the interference is in part arbitrary, care must be taken to select the most appropriate attributes.

If we were concerned only with regular trains of pulses, we might be inclined to use the peak amplitude of the pulses as a measure of intensity. But when the pulses are not all of the same amplitude, there is not a *single* peak amplitude but a distribution of peak amplitudes. Since it is sometimes difficult to decide what to call a peak and what not to call a peak, it is reasonable to consider not only peak amplitudes but all amplitudes—to take as the measure of intensity a quantity based on the distribution of the instantaneous amplitudes in the sample. Either the average power or the root mean square voltage of the interference is appropriate. The average power corresponds to the variance of the distribution of instantaneous amplitudes; the root mean square voltage corresponds to the standard deviation of the distribution.

Usually, we are interested only in that part of the interference spectrum which affects the receiver under test. Components of the interference which lie outside the over-all pass band of the receiver can be disregarded only if they do not interact with the signal or with noise components within the over-all pass band. If there is negligible interaction, the problem may be greatly simplified by considering only the interference within the pass band. In the experiments to be described, this simplification appeared to be justified. The intensity of the interference was specified, therefore, in terms of measurements made with the test receiver coupled to an output meter (RCA Type 302-A). Inasmuch as the pass band of the test receiver was approximately 10 kilocycles wide and, for each type of interference, the output meter was calibrated against a thermocouple meter, intensity is the average power (or, alternatively, the root mean square amplitude) in a 10-kilocycle band.

Two temporal characteristics of impulsive interference which must be considered in setting up a system of specification are pulse duration and pulse repetition frequency. Pulse duration is determined with the aid of a wide band oscilloscope or synchroscope, pulse repetition frequency with a wide band monitor receiver and a pulse counter. If the interference is a uniform train of rectangular pulses, it is uniquely determined by these two temporal quantities taken together with the intensitive quantity, average power. If the pulses are not rectangular or if the temporal sequence is irregular, further specification may be necessary. Actually, as long as the pulses are quite narrow, variations in their shape have no significant effects which are not taken into account in the determination of average power. The regularity or irregularity of the pulses is, however, a very important property of the interference.

In the present work, the interference was either as regular or as irregular as it could be made with the available techniques. As it turned out, some of the irregular impulsive interference appeared not to be entirely random, but it was very nearly so.

TESTS OF INTELLIGIBILITY

The first aim of the experiments was to determine, by means of articulation tests, which of the dimensions of variation are important, and which unimportant, in governing the effects of interference upon the reception of speech over an amplitude-modulation radio link. The second aim was to measure the effect upon reception of varying the interference in each important dimension. In the articulation tests, a talker read lists of monosyllabic words (PB lists)[2] to a group of listeners over an amplitude-modulation radio system set up in the laboratory. The listeners recorded the words as they heard them. The

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[2] J. P. Egan, *Articulation Testing Methods II*, OSRD Report No. 3802, PB 22848, November, 1944. Available through the Office of Technical Services, U. S. Department of Commerce, Washington, D. C.

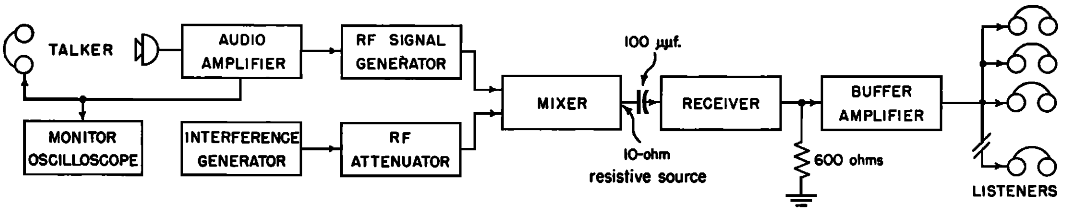

FIG. 1. Block diagram of the laboratory radio system.

percentage which they recorded correctly provided a measure of the intelligibility of speech under the conditions of the test.

Two different crews of listeners were used in the experiments. One was a group of 10 women (crew W) who had served as listeners in a number of investigations. The other was a group of six men (crew M), somewhat less highly experienced as listeners. Two talkers were used in the tests with listening-crew W, one talker in the tests with listening-crew M. The comparability of the two crews was determined empirically.

LABORATORY RADIO SYSTEM

The arrangement of the test set-up is shown in the block diagram of Fig. 1. An amplitude-modulated carrier (1.6 or 2.1 megacycles) was supplied by a General Radio Type 805-A signal generator. Speech modulation was provided by a talker using an RS 38-A carbon microphone, and monitoring his speech at a level suitable for communication under adverse conditions. The speech amplifier was adjusted to provide 100-percent modulation of the carrier on the instantaneous peaks of those test words which were average in peak-to-peak amplitude.

Interference was mixed with the modulated carrier and fed to the receiver, a superheterodyne, Navy Type ARB, Serial No. 3727, operated with manual control of volume. The selectivity curve and the audiofrequency response curve are shown in Fig. 2. An audio noise limiter was incorporated between the second detector and the audio amplifier. The limiter, designed by Carlton Wasmansdorff, was of the type described as a "low loss series limiter" in a recent paper by Toth.[3] Tests were made alternately with the limiter in operation and with the limiter disconnected.

In order to drive a number of headsets from the receiver without loading the output circuit unduly, a laboratory amplifier with high input impedance and low output impedance was used as a buffer (see Fig. 1). The signal developed by the receiver across the 600-ohm resistor was thus duplicated across each of the listeners' headsets, which consisted of dynamic earphones (Permoflux Type PDR-3), mounted in sponge-rubber cushions (MX-41/AR) and suspended by headbands (HB-7). In each articulation test, the speech-plus-interference output of the receiver was between 3 and 10 milliwatts in 600 ohms. The root mean square sound pressure level at the listeners' eardrums was approximately 115 db re 0.0002 dyne/cm^2.

CARRIER-TO-INTERFERENCE RATIO

In a simplified theoretical treatment, reception is assumed to be the same with a 10-microvolt carrier in the presence of 10-microvolt interference as it is with a 100-microvolt carrier in the presence of 100-microvolt interference. The first question to arise in connection with the articulation tests, therefore, was whether or not a similar simplification could be made with the laboratory radio system: Given a speech-

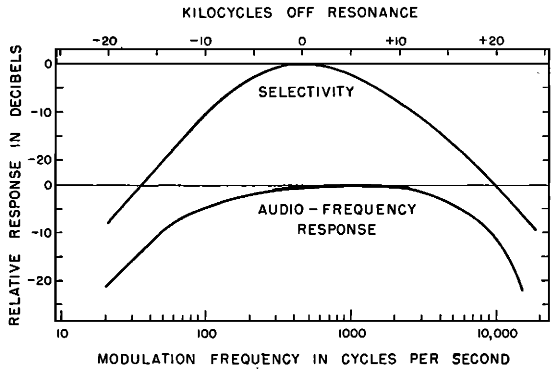

FIG. 2. Selectivity and audiofrequency response curves for the receiver used in the articulation tests.

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[3] E. Toth, Electronics, 114 (November 1946).

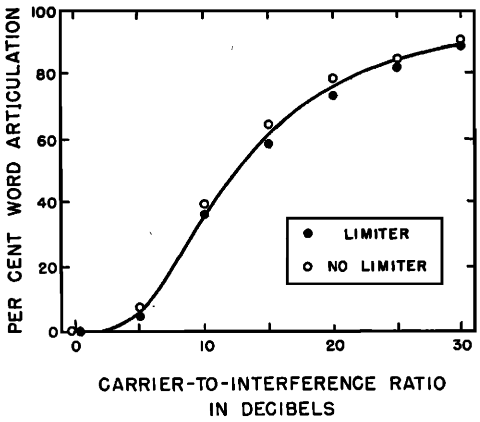

FIG. 3. The effect of fluctuation noise upon reception over the laboratory radio system. The curve shows the relation between *intelligibility* and the *carrier-to-interference ratio*. The series-diode noise limiter was ineffective against the fluctuation noise; actually, reception was very slightly worse with it than without it. Two talkers; listening-crew W.

modulated carrier and a particular type of interference, does intelligibility remain constant when the carrier-to-interference ratio is held constant, even though the absolute intensities of signal and interference are varied?

Assurance of an affirmative answer to the question was provided by physical tests which indicated that the input-output characteristic of the radio link, measured from the input of the modulator to the output of the detector, was linear over a reasonably wide range of carrier intensities, and that the inherent noise of the receiver was below 1 microvolt. Proof was provided by articulation measurements which were made with carrier-to-interference ratios of 0, 5, 10, 15, and 20 decibels. The speech carrier was held constant at 56 microvolts in one set of tests, and the interference (fluctuation noise) was held constant at 56 microvolts in another set. Analysis of the variance within the matrix of articulation scores showed that the carrier-to-interference ratio was a highly significant factor in determining intelligibility, but that—when the ratio was held constant—the absolute values of the signal and the noise were insignificant. These observations appear to justify the procedure of specifying the intensitive conditions of the articulation tests in terms of carrier-to-interference ratios. Thus, for a given type of interference, intelligibility can be represented as a function of the carrier-to-interference ratio, and this function is independent of the absolute magnitudes of the signal and the noise unless they are so weak that the inherent noise of the receiver must be taken into account, or so strong that some of the receiver circuits are overloaded.

Figure 3 shows the relation between percent word articulation and carrier-to-interference ratio for the type of interference known as fluctuation noise. Since it can be thought of as consisting of an exceedingly large number of very brief pulses, and since its spectrum is continuous and uniform, fluctuation noise is frequently regarded as a standard of reference among interferences. The curve of Fig. 3 may be taken, therefore, as a reference curve for reception over an amplitude-modulation radio system. About 50 percent of the words are correctly understood when the carrier is 12 db more intense than the interference.

PULSE DURATION

If the duration of an interference pulse is considerably less than that of the shortest pulse which can pass through the tuned circuits of the receiver, the audio wave delivered to the listener's ear is dependent only upon the area and not upon the shape of the interference pulse. Thus, if the pulse is rectangular, a doubling of its duration can be compensated exactly by a halving of its amplitude.[4] It would not be expected, therefore, that pulse duration would have any effect upon intelligibility as long as the pulses are kept short and the carrier-to-interference ratio is held constant.

However, as soon as the duration of the input pulses approaches in magnitude the reciprocal of the band width of the receiver, further increases in duration begin to affect the form of the audio wave. (See insets, Fig. 4.) If the input pulses are made long enough, two separate pulses appear in the audio wave, and the p.r.f. of the receiver output becomes twice that of the radiofrequency interference. For this reason, it was of interest to determine empirically the relation between intelligibility and the duration of the pulses which comprise the interference.

Articulation tests were conducted with interference consisting of rectangular pulses in regular sequence at a p.r.f. of 1000 per second. Pulse duration was varied from one test to the next. A Colonial Pulse Generator, Model 700A, provided the pulses with durations below 120 microseconds; a laboratory generator, PAL Type 430, was used for longer pulses. The carrier-to-interference ratio was held constant at 0 db. In all of the tests, the noise limiter was disconnected.

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[4] S. S. Stevens, J. Miller, and I. Truscott, J. Acous. Soc. Am. 18, 418 (1946).

The results of the articulation tests are shown in Fig. 4. It is seen that the datum points fall along a horizontal line at approximately 40-percent word articulation. With the average power of the interference in the pass band held constant, 0.4-microsecond pulses had approximately the same effect upon intelligibility as did 500-microsecond square waves. Statistical analysis confirms the conclusion based on inspection: pulse duration was not a significant variable. There is reason to believe that, if the noise limiter had been used, the same conclusion could have been drawn for pulse durations at least up to 100 microseconds.

The spectral distribution of the energy in a train of regularly spaced, rectangular pulses is characterized by maxima and null points, the latter occurring at multiples of the reciprocal of the pulse duration. When the pulse duration is varied, the whole pattern of maxima and null points in the interference spectrum shifts along the frequency scale. If the pulse duration is such that a *null point* falls within the pass band of the receiver, only a very small part of the total interference power (that within the pass band of the receiver on either side of the null point) is converted into audio noise. If the pulse duration is such that a *maximum* falls within the pass band of the receiver, a much larger fraction of the total interference power passes through the resonant circuits. The question therefore arises: if allowance is made for the difference in intensity, is the part of the interference spectrum near a null point equal in interference value to the part near a maximum? The over-all intensity of the interference is adjusted by means of an attenuator to make the intensity within the pass band the same in the region of the null point as in the region of the maximum. The question is whether, after such adjustment, the effects upon intelligibility are equivalent.

Again with two talkers and listening-crew W, articulation tests were conducted with the limiter inoperative, with the receiver tuned to 2.1 megacycles, and with pulse durations of 0.75, 0.95, and 1.15 microsecond. With 0.95-microsecond pulses, the pass band of the receiver spanned a null point. With 0.75- and 1.15-microsecond pulses, the receiver was tuned near maxima in the interference spectrum. The average articulation scores for the three pulse durations were: 0.75 microsecond, 27 percent; 0.95 microsecond, 28 percent; and 1.15 microsecond, 29 percent. The differences are clearly insignificant.

Thus the conclusion would appear to be justified that, if the ratio of the carrier power to the interference power within the pass band is held constant, variation in the duration of the interference pulses produces no marked effect upon intelligibility. An exception to this rule probably occurs when a noise limiter is used and when the duration of the input pulses is of the same order as that of the output pulses.

PULSE REPETITION FREQUENCY

If interference pulses occur at a repetition frequency of 10 per second or lower, they may be annoying, but they do not impair to any marked degree the intelligibility of speech heard over a

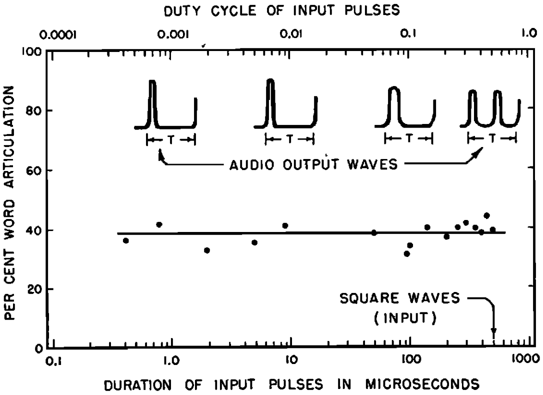

FIG. 4. Showing that intelligibility remains essentially constant despite wide variation in the duration of the input pulses. The interference consisted of rectangular pulses occurring in regular succession at a repetition frequency of 1000 per second. The carrier-to-interference ratio was held at 0 decibel by decreasing pulse amplitude to compensate for increasing pulse duration. Audio output waves corresponding to input pulse durations of 1.0, 10, 100, and 500 microseconds are shown as insets. The period *T* is 1 millisecond. Two talkers; listening-crew W.

properly designed receiver. Before the low p.r.f. pulses can reach an amplitude at which they might mask speech, they are limited by overload in some part of the communication circuit. If great care were taken to make the amplifying stages linear over a wide enough range to pass such pulses without amplitude limiting, the overload would occur in the listener's ears. The listener's reports of tickle, pressure, and pain discourage the use of his ears as amplitude limiters, of course; but the fact remains that moderately strong speech cannot be made unintelligible by short pulses at low p.r.f. no matter how intense the pulses.

If, on the other hand, the interference pulses occur at very high p.r.f., at a p.r.f. numerically of the same order as the band width of the receiver in cycles per second, and if they occur in a regular train, their effect is for all practical purposes indeterminate. When the p.r.f. is very high, the harmonics of the interference are widely spaced, and it may happen that all of them fall outside the pass band of the receiver. If just one of the harmonics happens to fall within the pass band, the difference between its frequency and that of the carrier is very important. Marked interference occurs if the separation is between 500 and 1000 cycles per second; very little interference is noted if the separation is greater than 2000.[5] If the harmonic should coincide with the carrier, either addition or cancellation might occur, depending upon the phase relation between the carrier and the interference. Thus the interference value of regular pulses at high p.r.f. depends upon the relation between the carrier frequency and the frequencies of certain

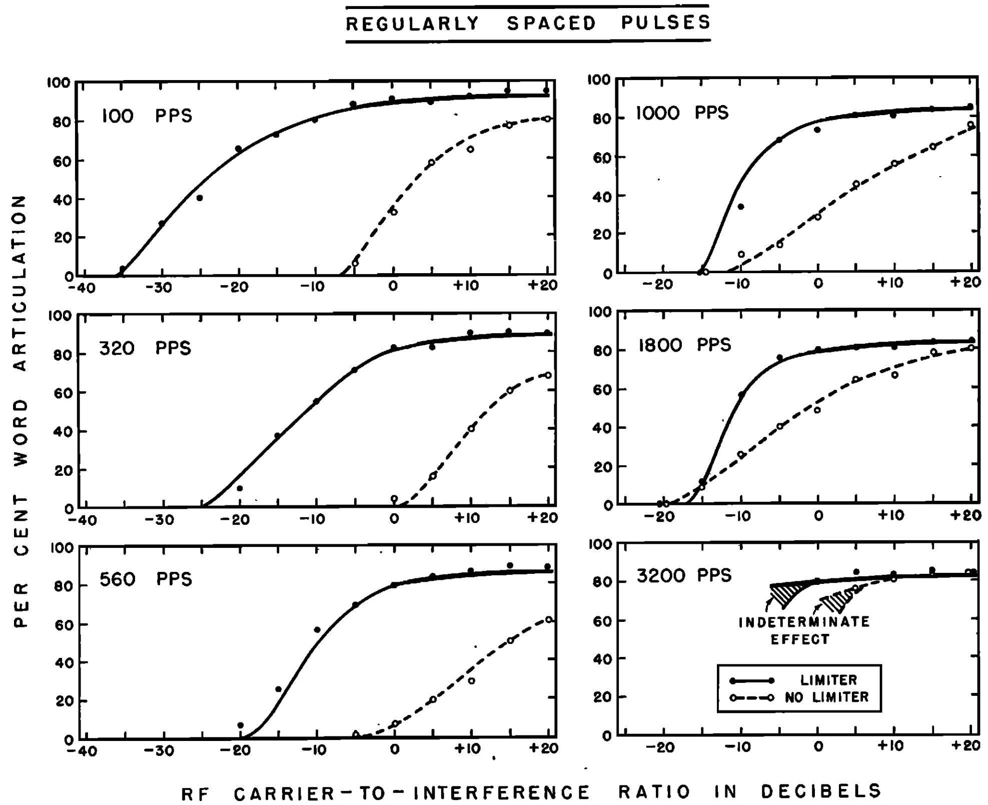

FIG. 5. Effects of *regular* impulsive interference at various pulse repetition frequencies. The curves show how intelligibility increases with increasing carrier-to-interference ratio. With p.r.f.'s below 560, the noise limiter was very effective; it provided usable reception (50-percent word articulation) with a carrier about 25 decibels weaker than that required without the limiter. With higher p.r.f.'s, the limiter was less effective. Two talkers; listening-crew W.

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[5] J. C. R. Licklider and S. J. Goffard, *The Performance of Counter-modulation and Static-cancelling Circuits in Aircraft Radio Receiver AN/ARR-15*, Harvard Psycho-Acoustic Laboratory Report PNR-9, March 1946.

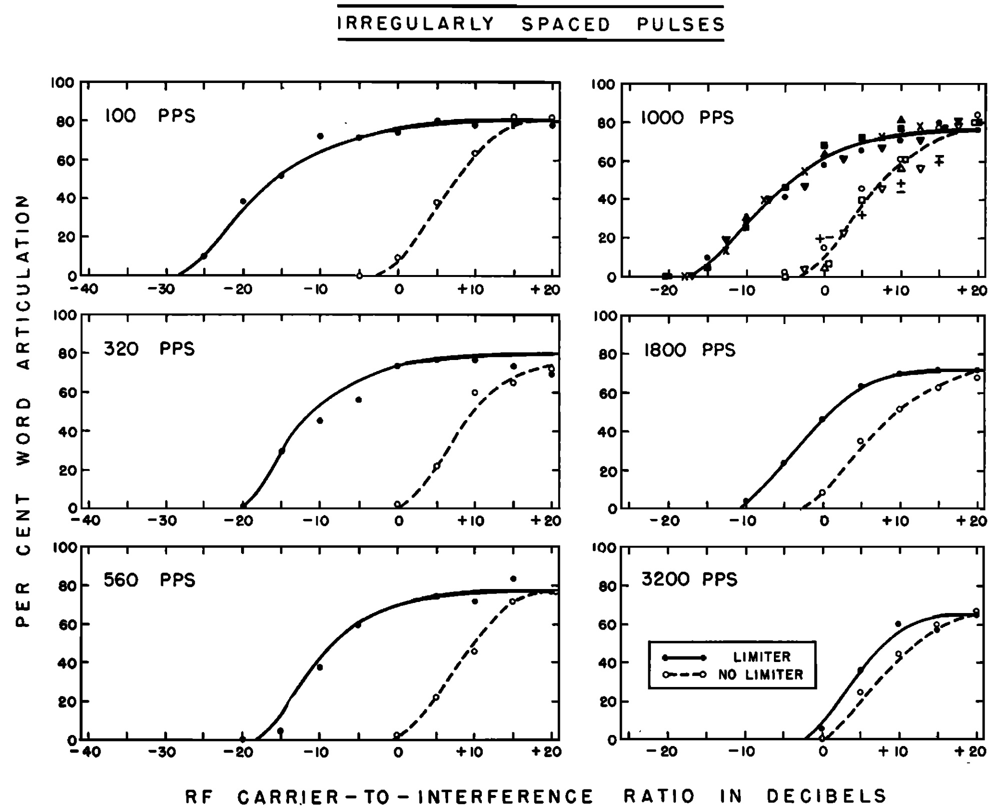

FIG. 6. Effects of *irregular* impulsive interference at various repetition frequencies. The curves appear at first glance to be roughly similar to those for regular interference (cf. Fig. 5), but more careful comparison reveals several differences: On the whole, the irregular pulses have slightly higher interference value than the regular pulses. At high p.r.f., irregular pulses become almost as interfering as fluctuation noise, whereas the effect of regular pulses becomes indeterminate. The slope of the "no limiter" curve for irregular pulses is approximately constant, whereas the slope of the corresponding curve for regular pulses varies as a function of p.r.f. One talker; listening-crew M.

harmonics of the interference. And, in the event of coincidence between the carrier and one of the harmonics, the interference value depends upon relative phase.

In between the very low and the very high p.r.f.'s, there is a range which can be studied with the aid of articulation tests. For a receiver with a 10-kilocycle pass band, this range extends approximately from 100 to 3200 pulses per second. Articulation tests were conducted, therefore, with p.r.f.'s of 100, 320, 560, 1000, 1800, and 3200, and with a wide range of carrier-to-interference ratios at each p.r.f. The source of the interference was the Colonial Pulse Generator, set for 1.15-microsecond pulse duration. The test receiver was tuned to 2.1 megacycles. The results are shown in Fig. 5.

In Fig. 5, there are two curves for each p.r.f., a solid curve to show the relation between intelligibility and carrier-to-interference ratio in tests with the noise limiter in operation, a dashed curve to show the relation in tests with the limiter disconnected. The noise limiter was highly effective against low p.r.f. interference and less effective against high p.r.f. interference. A similar relation between the effectiveness of amplitude limiting and the p.r.f. of the interference has been noted in tests of radio range receivers.[6] On the whole, the limiter provided a marked improvement in performance. It is clear that the relation between intelligibility and carrier-to-interference ratio depends to a pronounced degree upon the linearity of the receiver circuits, and that the more linear circuit was by no means the better for reception in the presence of severe impulse noise.

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[6] S. J. Goffard and J. C. R. Licklider, *Effects of Static on Radio Range Performance*, Harvard Psycho-Acoustic Laboratory Report PNR-10, March 1946.

In the tests with the limiter disconnected, an attempt was made to avoid overloading any of the receiver circuits. The dissimilarities among the dashed curves in Fig. 5 are interpreted, therefore, as showing that even with a linear receiver the interference value of impulse noise depends upon its p.r.f. The most deleterious p.r.f. is in the neighborhood of 500 pulses per second.

IRREGULARITY OF PULSES

Irregular impulse interference is encountered even more frequently than regular impulse interference. Much of the interference subsumed under the term *atmospherics* is impulsive, and irregularity is one of its most characteristic features. Irregular radio interference is often not completely random. Sometimes the deviation from complete randomness is in the direction of clustering, as in "bursts" and "grinders." Sometimes it is in the direction of uniform spacing, as when aircraft precipitation static takes on a tonal quality. For this reason, "irregular" is more accurately descriptive than is "random."

The interference used in the tests to be described was generated with the aid of an ionization-noise generator and a spark coil and gap.[7] Very sharp electrical pulses were produced whenever the ionization-noise voltage exceeded the breakdown voltage of the spark gap. Because the spectrum of the ionization noise was limited to the frequency range below 10,000 cycles per second, and because of ionization effects in the spark gap, the sequence of the pulses cannot be said to be completely random. Actually, the irregularity appeared to be quite similar to that of thunderstorm static.

Articulation tests were conducted to determine the effect of this irregularity upon the interference value of the pulses. The p.r.f.'s and the carrier-to-interference ratios were the same as those used in the tests with regular pulses. Unfortunately, the talkers and listeners employed in the previous tests were not available; a different talker and a different listening-crew (M) were used.

The results of the tests are shown in Fig. 6. Comparison of Fig. 6 with Fig. 5 indicates that, in the presence of irregular pulses as in the presence of regular pulses, the effectiveness of the limiter declines with increasing p.r.f. With the limiter disconnected, there is considerably less variation of performance with changes in p.r.f. On the whole, the articulation scores are somewhat, though not markedly, lower in the tests with irregular pulses than in the tests with regular pulses.

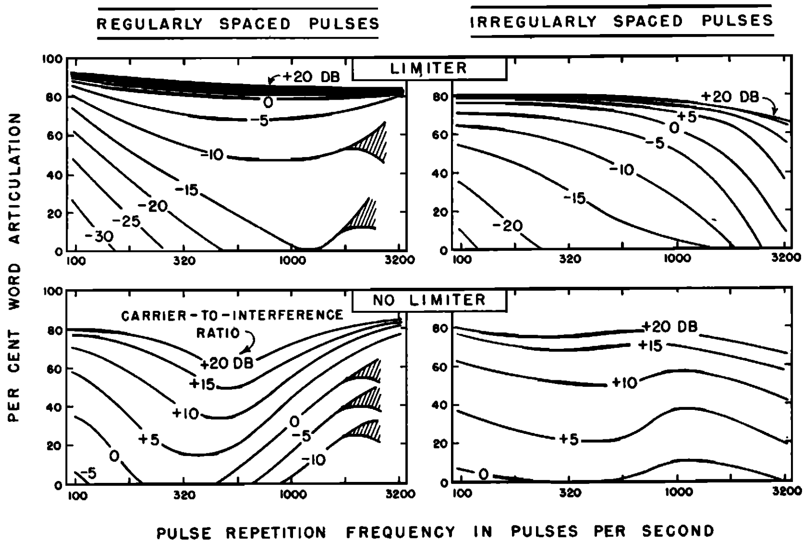

FIG. 7. Showing the relations between intelligibility and p.r.f. for regular and for irregular pulses. The upper graphs are based on the tests with the noise limiter in operation, the lower graphs on tests with the noise limiter disconnected. These curves are derived from those of Figs. 5 and 6.

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[7] J. C. R. Licklider and E. B. Newman, "Static for laboratory tests of radio receivers," Electronics 98 (June 1947).

In view of the fact that random audio pulses mask speech much more severely than do regular audio pulses, it is at first thought surprising that the curves of Figs. 5 and 6 are as similar as they are. Stevens, Miller, and Truscott[8] found that under certain conditions randomized audio pulses were as much as 50 decibels more effective than regular audio pulses in masking speech. No such difference as this appeared in the tests with radio interference.

The difference between the audio and the radio results is probably to be explained in terms of the fact that, whereas aural masking was the only factor reducing intelligibility in the audio tests, an additional factor operates in the radio situation. This additional factor, intermodulation in the detector circuits of the receiver, distorts the speech and introduces frequency components which would not appear if the speech and noise were detected separately. Reception over a radio link operating in the presence of electrical interference thus tends to be poor for two reasons: (1) in the receiver, intermodulation between the signal and the interference distorts the speech, (2) in the ear, noise and distortion products mask what is left of the speech. The intermodulation appears to cause at least as much impairment of intelligibility when the interference is regular as it does when the interference is irregular, and in the presence of regular interference it is a more important factor than aural masking. It follows, therefore, that, if audio listening tests and radio listening tests were conducted at the same speech-to-noise ratio (allowance being made for the degree of modulation in specifying the ratio in the radio tests), the audio tests should yield the higher articulation scores, and the difference between the audio scores and the radio scores should be greater in the presence of regular interference than in the presence of irregular interference.

In the upper right-hand graph of Fig. 6 are shown datum points from a number of experiments with irregular pulses at a p.r.f. of 1000. The circles (filled and unfilled) represent the scores of crew M. The squares represent the scores of crew W. The other datum points were obtained with other receivers and with other personnel. This empirical evidence of the repeatability of the results is probably of greater practical value than an estimate based on the internal consistency of a single set of experiments. As a rough rule, it appears reasonable to regard a consistent horizontal displacement of 3 decibels, or a consistent vertical displacement of 15 articulation points as due to a significant variable in the experiment.

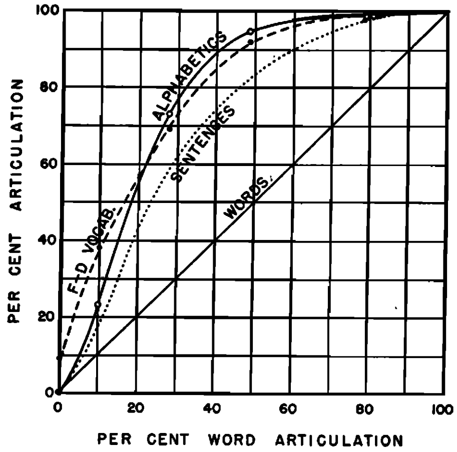

FIG. 8. Curves showing that meaningful sentences and special vocabularies are more intelligible than the monosyllabic words of the test lists. These curves are useful in predicting performance from Fig. 7.

According to this criterion, the p.r.f. of the interference is clearly a significant variable if the receiver is equipped with an amplitude limiter, no matter whether the interference is regular or irregular. Without a limiter, p.r.f. is a significant variable if the interference is regular, but it is relatively insignificant if the interference is irregular. These relations between intelligibility and p.r.f. are shown graphically in Fig. 7, in which the curves of Figs. 5 and 6 are replotted with carrier-to-interference ratio as a parameter. It is probable that the curves of the lower right-hand graph would have been horizontal straight lines if the interference had been entirely random.

DISCUSSION OF RESULTS

The results of the articulation tests provide a basis for estimating the performance to be expected from a conventional amplitude-modulation system operating against specified impulsive interference. If the performance is to be judged in terms of the intelligibility of speech material more meaningful than isolated test words, Fig. 8 is of interest. It shows how the intelligibility of sentences and of special vocabularies compares with that of the test words, i.e., of monosyllabic words heard out of context. The data for the alphabetic equivalents ("Able" for A, "Baker" for B, "Charlie" for C, etc.) and for the Fighter-Director Vocabulary (used to direct fighter planes via VHF radio from aircraft carriers) were obtained with the laboratory radio system. The curve for sentences is an estimate based on tests with audio circuits.[9,10]

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[8] S. S. Stevens, J. Miller, and I. Truscott, J. Acous. Soc. Am. 18, 418 (1946).

When heard under identical conditions, the alphabetic equivalents and the Fighter-Director Vocabulary are much more easily understood than are the discrete words used in the articulation tests. Sentences are also more easily understood than the test words because the listener can frequently "fill in" from the context. Thus, although 50-percent word articulation is usually taken as the lower limit of usable communication, it is clear that some information can be conveyed over a communication system functioning at a level of 25- or 30-percent word articulation.

The left-hand curves of Fig. 5 indicate that, with the help of a simple noise limiter, a conventional amplitude-modulation system can, under certain conditions, provide usable communication with a carrier-to-interference ratio as low as *minus* 20 decibels. Even without a noise limiter, 50-percent word articulation was obtained in most of the tests with carrier-to-noise ratios between 0 and 12 decibels. These figures stand in marked contrast to the values of 30 decibels,[11,12] 40 decibels,[13] and more,[14] cited as defining the minimum tolerable ratio of carrier to noise in broadcast reception. But broadcast reception can by no means be evaluated simply in terms of intelligibility.

It is of greater interest to compare the results of the present tests with criteria of performance which have been used in commercial and in military communication. In most instances, intensity has been the only characteristic of the interference taken into account. Various methods of measurement and various values of minimum tolerable carrier-to-interference ratio have been adopted. Little consideration has been given to p.r.f. or to the degree of regularity of the interference.

The most thorough treatment of the problem appears to have been made in connection with ship-shore and overseas radio. Even this treatment, however, fails to take into account specific non-intensitive characteristics of the interference. Actually, two different functions relating intelligibility and carrier-to-interference ratio have been used, one as the basis for ratings of "circuit merit",[15] and the other to establish the requirements for emergency communication on the Great Lakes.[16] Ratings of "circuit merit" are made in accordance with the following table:

Circuit merit (1)	Percent speech intelligibility (2)	Performance (3)	Carrier-to-interference ratio (4)
1	0–20	Hopeless	Below 8 db
2	20–40	Poor (uncommercial)	8 to 16 db
3	40–60	Fair (commercial)	12 to 22 db
4	60–80	Good (commercial)	20 to 32 db
5	80–100	Excellent (commercial)	Above 30 db

The relation between intelligibility and carrier-to-interference ratio given in the table agrees fairly closely with that shown in Fig. 3, in which the interference was fluctuation noise. The results shown in Figs. 5–7 would suggest, however, that the relation between intelligibility and carrier-to-interference ratio is more highly dependent upon non-intensitive characteristics of the interference than the ranges in the table indicate.

The results of the tests conducted on the Great Lakes indicated that 84-percent sentence

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[9] H. Pender and K. McIlwain, *Electrical Engineers' Handbook* (John Wiley and Sons, Inc., New York, 1936), Vol. V, Chap. 9, 26.

[10] S. S. Stevens, J. Miller, J. P. Egan, T. H. Waterman, and S. C. Rome, *Articulation Testing Methods*, OSRD Report No. 383, PB 22916, February 1942. Available through the Office of Technical Services, U. S. Department of Commerce, Washington, D. C.

[11] C. V. Aggers, D. E. Foster, and C. S. Young, Elec. Eng. **59**, 178 (1940).

[12] M. G. Crosby, RCA Rev. **4**, 349 (1940).

[13] Committee of the British Institution of Electrical Engineers, J. Inst. Elec. Eng. **79**, 206 (1936).

[14] R. Brown, J. Inst. Elec. Eng. **83**, 395 (1938).

[15] D. Talley, Q.S.T. **30**, 62 (1947).

[16] Federal Communications Commission. A Report of the Marine Section, Safety and Special Services Division, on the Great Lakes Engineering Study of 1941, Washington, May 1942.

intelligibility, which in Fig. 8 corresponds to 50-percent word articulation, was possible with a ratio of carrier to interference of 21 decibels, the interference (atmospherics) being measured in a 1-kilocycle band. For a 10-kilocycle band of interference, the corresponding carrier-to-noise ratio is 11 decibels. This value is very close to the values indicated by the curves of Figs. 3 and 6 which show the relation between word articulation and carrier-to-interference ratio in the tests with the noise limiter inoperative.

The present data emphasize that the amplitude-handling characteristics of the receiver must be taken into consideration if estimates of performance are to be of any value at all. This is not simply a matter of noting whether or not the receiver is equipped with a noise limiter, because all limiters are not equally effective, and because, even without noise limiters, good operators frequently obtain limiting in intermediate-frequency or in audiofrequency circuits by overdriving their receivers. As a rough rule, amplitude limiting can be disregarded in predicting performance if the p.r.f. of the interference (in pulses per second) is one-third as high as the IF band width of the receiver (in cycles per second). If the p.r.f. is low, however, the amplitude-limiting characteristic of the receiver is probably the most important factor governing performance. This discussion assumes that if circuits such as automatic volume controls and squelches are used, they are free from special vulnerabilities which would impair performance in the presence of impulsive interference.

CONCLUSIONS

The results of word articulation tests, conducted in the laboratory with an amplitude-modulation radio system operating in the presence of electrical interference, lead to the following conclusions:

(1) The characteristics of impulsive interference which determine its interference value include intensity, pulse repetition frequency, and degree of regularity. On the whole, the duration of the pulses and the shape of the interference spectrum are not major factors except insofar as they affect the intensity of the interference within the pass band of the receiver.

(2) Usable communication—50-percent intelligibility in tests with unrelated monosyllabic words—was obtained with carrier-to-interference ratios ranging from *minus* 20 decibels to *plus* 15 decibels, depending upon the type of interference and the amplitude-handling characteristics of the receiver. Thus performance cannot be predicted accurately on the basis of carrier-to-interference ratio alone.

(3) The relation between pulse repetition frequency and interference value depends upon whether or not amplitude limiting occurs in the receiver. When there is no amplitude limiting, the most detrimental pulse repetition frequency is in the neighborhood of 500 pulses per second. When a limiter is used, interference value increases with increasing p.r.f.

(4) Radiofrequency interference consisting of pulses in regular sequence gives rise to a periodic audio wave which sounds like a musical tone. If the number and the shape of the pulses which constitute the radiofrequency interference are held constant, but their times of occurrence are randomized, the audio wave loses its tonal quality. The irregularly-spaced pulses sound like "static" or like "white" noise, depending upon the repetition frequency. Irregular interference is on the whole more detrimental than regular interference.

(5) With the aid of the curves of Fig. 7, it is possible to predict the performance of a conventional amplitude-modulation radio system if the band width is approximately 10 kilocycles and if the important characteristics of the interference are specified.

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Effects of Impulsive Interference upon A-M Voice Communication*

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The degree to which noise impairs the intelligibility of speech depends upon the characteristics of the noise. In this paper, which is concerned with electrical interference and radio communication, the questions are: (1) "what characteristics of the noise determine the degree of impairment," and (2) "what are the functional relations between intelligibility and the important characteristics of the noise?" Answers to these questions were obtained with the aid of articulation tests, conducted with a typical amplitude-modulation system and with a variety of electrical interferences.

INTRODUCTION

DURING the war, the problem of electrical interference in radio communication became more serious by the month. Radars, IFF's, electronic altimeters, pulse navigation systems, aircraft precipitation static, and jammers added their voices to the discordant chorus which, before the war, had been created largely by electrical machinery, ignition systems, diathermy apparatus, and atmospherics. Interference reduction programs were set up. Maximum noise specifications were written. The basic question arose: "How much interference can be tolerated?"

This question was short, but it was not simple. Even its statement in relative terms—how high a ratio of noise to signal can be tolerated—did not make it easy to answer. There were too many types of modulation, too many kinds of interference, and too many levels of tolerance.

The question did not receive an entirely satisfactory answer. Nevertheless, the asking served to point out how little was known, even for the simplest radio systems, about the relation between the intelligibility of speech heard over a radio link and the carrier-to-interference ratio. This paper is concerned with that relation as it obtains for a typical amplitude-modulation system operating in the presence of impulsive interference. It is concerned, further, with the way in which the relation between intelligibility and the carrier-to-interference ratio depends upon several non-intensitive characteristics of the interference.

DIMENSIONS OF IMPULSE INTERFERENCE

Impulse noise is defined as noise arising from disturbances which are essentially instantaneous. Thus interference from ignition systems and from electrical machines with sparking contacts is impulsive. The trains of pulses generated by the modulators of radars and certain other pulse-transmission systems also are included within the definition; the durations of the pulses are very short relative to the durations of the audio-frequency waves which they cause in the output circuits of radio receivers. Atmospheric static and aircraft precipitation static are also to some degree impulsive, and even fluctuation noise ("white" noise) may be thought of as an extremely dense concentration of extremely short pulses, occurring in random sequence.

Samples of impulse noise may differ from one another in a number of ways. First, there are samples in which the pulses are all alike and essentially rectangular in shape, following one another in regular succession. In such samples, the possible dimensions of variation include pulse amplitude, pulse duration, pulse repetition frequency (p.r.f.), and a number of other characteristics which are fixed if the amplitude, duration, and repetition frequency of the pulses are specified.[1] There are other samples of impulse noise in which the individual pulses are *not* all alike, or in which they are *not* essentially rectangular in shape, or in which they do *not* occur in regular succession. Innumerable patterns of this type are of course possible. Fortunately, however, by no means all of the possible patterns are encountered as interference with radio communication.

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* This work was done under Contract N5ori-76 between the U. S. Navy, Office of Naval Research, and Harvard University. This is Report PNR-32 from the Harvard Psycho-Acoustic Laboratory.

** Now at the University of Minnesota.

[1] S. S. Stevens, J. Miller, and I. Truscott, J. Acous. Soc. Am. 18, 418 (1946).

The first step in working with radio interference is to set up a system of specification which takes into account the modes of variation just enumerated. The dimensions of such a system fall into two broad classes, intensitive and temporal. Since the selection of the particular intensitive and temporal attributes to be used in specifying the interference is in part arbitrary, care must be taken to select the most appropriate attributes.

If we were concerned only with regular trains of pulses, we might be inclined to use the peak amplitude of the pulses as a measure of intensity. But when the pulses are not all of the same amplitude, there is not a *single* peak amplitude but a distribution of peak amplitudes. Since it is sometimes difficult to decide what to call a peak and what not to call a peak, it is reasonable to consider not only peak amplitudes but all amplitudes—to take as the measure of intensity a quantity based on the distribution of the instantaneous amplitudes in the sample. Either the average power or the root mean square voltage of the interference is appropriate. The average power corresponds to the variance of the distribution of instantaneous amplitudes; the root mean square voltage corresponds to the standard deviation of the distribution.

Usually, we are interested only in that part of the interference spectrum which affects the receiver under test. Components of the interference which lie outside the over-all pass band of the receiver can be disregarded only if they do not interact with the signal or with noise components within the over-all pass band. If there is negligible interaction, the problem may be greatly simplified by considering only the interference within the pass band. In the experiments to be described, this simplification appeared to be justified. The intensity of the interference was specified, therefore, in terms of measurements made with the test receiver coupled to an output meter (RCA Type 302-A). Inasmuch as the pass band of the test receiver was approximately 10 kilocycles wide and, for each type of interference, the output meter was calibrated against a thermocouple meter, intensity is the average power (or, alternatively, the root mean square amplitude) in a 10-kilocycle band.

Two temporal characteristics of impulsive interference which must be considered in setting up a system of specification are pulse duration and pulse repetition frequency. Pulse duration is determined with the aid of a wide band oscilloscope or synchroscope, pulse repetition frequency with a wide band monitor receiver and a pulse counter. If the interference is a uniform train of rectangular pulses, it is uniquely determined by these two temporal quantities taken together with the intensitive quantity, average power. If the pulses are not rectangular or if the temporal sequence is irregular, further specification may be necessary. Actually, as long as the pulses are quite narrow, variations in their shape have no significant effects which are not taken into account in the determination of average power. The regularity or irregularity of the pulses is, however, a very important property of the interference.

In the present work, the interference was either as regular or as irregular as it could be made with the available techniques. As it turned out, some of the irregular impulsive interference appeared not to be entirely random, but it was very nearly so.

TESTS OF INTELLIGIBILITY

The first aim of the experiments was to determine, by means of articulation tests, which of the dimensions of variation are important, and which unimportant, in governing the effects of interference upon the reception of speech over an amplitude-modulation radio link. The second aim was to measure the effect upon reception of varying the interference in each important dimension. In the articulation tests, a talker read lists of monosyllabic words (PB lists)[2] to a group of listeners over an amplitude-modulation radio system set up in the laboratory. The listeners recorded the words as they heard them. The

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[2] J. P. Egan, *Articulation Testing Methods II*, OSRD Report No. 3802, PB 22848, November, 1944. Available through the Office of Technical Services, U. S. Department of Commerce, Washington, D. C.

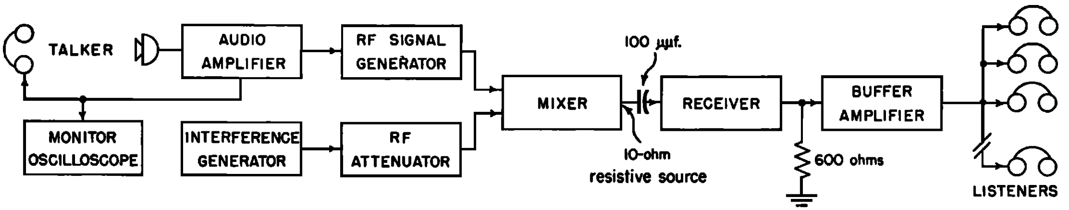

FIG. 1. Block diagram of the laboratory radio system.

percentage which they recorded correctly provided a measure of the intelligibility of speech under the conditions of the test.

Two different crews of listeners were used in the experiments. One was a group of 10 women (crew W) who had served as listeners in a number of investigations. The other was a group of six men (crew M), somewhat less highly experienced as listeners. Two talkers were used in the tests with listening-crew W, one talker in the tests with listening-crew M. The comparability of the two crews was determined empirically.

LABORATORY RADIO SYSTEM

The arrangement of the test set-up is shown in the block diagram of Fig. 1. An amplitude-modulated carrier (1.6 or 2.1 megacycles) was supplied by a General Radio Type 805-A signal generator. Speech modulation was provided by a talker using an RS 38-A carbon microphone, and monitoring his speech at a level suitable for communication under adverse conditions. The speech amplifier was adjusted to provide 100-percent modulation of the carrier on the instantaneous peaks of those test words which were average in peak-to-peak amplitude.

Interference was mixed with the modulated carrier and fed to the receiver, a superheterodyne, Navy Type ARB, Serial No. 3727, operated with manual control of volume. The selectivity curve and the audiofrequency response curve are shown in Fig. 2. An audio noise limiter was incorporated between the second detector and the audio amplifier. The limiter, designed by Carlton Wasmansdorff, was of the type described as a "low loss series limiter" in a recent paper by Toth.[3] Tests were made alternately with the limiter in operation and with the limiter disconnected.

In order to drive a number of headsets from the receiver without loading the output circuit unduly, a laboratory amplifier with high input impedance and low output impedance was used as a buffer (see Fig. 1). The signal developed by the receiver across the 600-ohm resistor was thus duplicated across each of the listeners' headsets, which consisted of dynamic earphones (Permoflux Type PDR-3), mounted in sponge-rubber cushions (MX-41/AR) and suspended by headbands (HB-7). In each articulation test, the speech-plus-interference output of the receiver was between 3 and 10 milliwatts in 600 ohms. The root mean square sound pressure level at the listeners' eardrums was approximately 115 db re 0.0002 dyne/cm^2.

CARRIER-TO-INTERFERENCE RATIO

In a simplified theoretical treatment, reception is assumed to be the same with a 10-microvolt carrier in the presence of 10-microvolt interference as it is with a 100-microvolt carrier in the presence of 100-microvolt interference. The first question to arise in connection with the articulation tests, therefore, was whether or not a similar simplification could be made with the laboratory radio system: Given a speech-

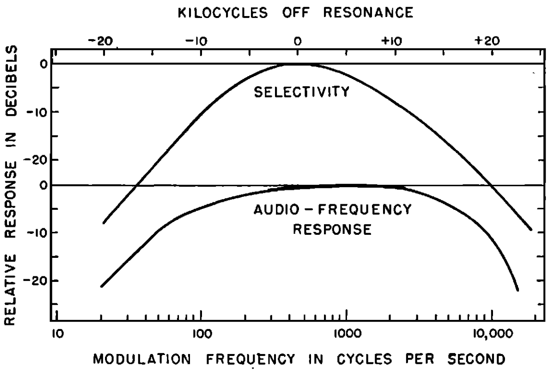

FIG. 2. Selectivity and audiofrequency response curves for the receiver used in the articulation tests.

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[3] E. Toth, Electronics, 114 (November 1946).

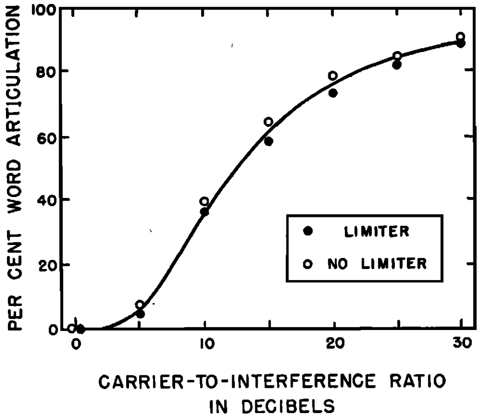

FIG. 3. The effect of fluctuation noise upon reception over the laboratory radio system. The curve shows the relation between *intelligibility* and the *carrier-to-interference ratio*. The series-diode noise limiter was ineffective against the fluctuation noise; actually, reception was very slightly worse with it than without it. Two talkers; listening-crew W.

modulated carrier and a particular type of interference, does intelligibility remain constant when the carrier-to-interference ratio is held constant, even though the absolute intensities of signal and interference are varied?

Assurance of an affirmative answer to the question was provided by physical tests which indicated that the input-output characteristic of the radio link, measured from the input of the modulator to the output of the detector, was linear over a reasonably wide range of carrier intensities, and that the inherent noise of the receiver was below 1 microvolt. Proof was provided by articulation measurements which were made with carrier-to-interference ratios of 0, 5, 10, 15, and 20 decibels. The speech carrier was held constant at 56 microvolts in one set of tests, and the interference (fluctuation noise) was held constant at 56 microvolts in another set. Analysis of the variance within the matrix of articulation scores showed that the carrier-to-interference ratio was a highly significant factor in determining intelligibility, but that—when the ratio was held constant—the absolute values of the signal and the noise were insignificant. These observations appear to justify the procedure of specifying the intensitive conditions of the articulation tests in terms of carrier-to-interference ratios. Thus, for a given type of interference, intelligibility can be represented as a function of the carrier-to-interference ratio, and this function is independent of the absolute magnitudes of the signal and the noise unless they are so weak that the inherent noise of the receiver must be taken into account, or so strong that some of the receiver circuits are overloaded.

Figure 3 shows the relation between percent word articulation and carrier-to-interference ratio for the type of interference known as fluctuation noise. Since it can be thought of as consisting of an exceedingly large number of very brief pulses, and since its spectrum is continuous and uniform, fluctuation noise is frequently regarded as a standard of reference among interferences. The curve of Fig. 3 may be taken, therefore, as a reference curve for reception over an amplitude-modulation radio system. About 50 percent of the words are correctly understood when the carrier is 12 db more intense than the interference.

PULSE DURATION

If the duration of an interference pulse is considerably less than that of the shortest pulse which can pass through the tuned circuits of the receiver, the audio wave delivered to the listener's ear is dependent only upon the area and not upon the shape of the interference pulse. Thus, if the pulse is rectangular, a doubling of its duration can be compensated exactly by a halving of its amplitude.[4] It would not be expected, therefore, that pulse duration would have any effect upon intelligibility as long as the pulses are kept short and the carrier-to-interference ratio is held constant.

However, as soon as the duration of the input pulses approaches in magnitude the reciprocal of the band width of the receiver, further increases in duration begin to affect the form of the audio wave. (See insets, Fig. 4.) If the input pulses are made long enough, two separate pulses appear in the audio wave, and the p.r.f. of the receiver output becomes twice that of the radiofrequency interference. For this reason, it was of interest to determine empirically the relation between intelligibility and the duration of the pulses which comprise the interference.

Articulation tests were conducted with interference consisting of rectangular pulses in regular sequence at a p.r.f. of 1000 per second. Pulse duration was varied from one test to the next. A Colonial Pulse Generator, Model 700A, provided the pulses with durations below 120 microseconds; a laboratory generator, PAL Type 430, was used for longer pulses. The carrier-to-interference ratio was held constant at 0 db. In all of the tests, the noise limiter was disconnected.

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[4] S. S. Stevens, J. Miller, and I. Truscott, J. Acous. Soc. Am. 18, 418 (1946).

The results of the articulation tests are shown in Fig. 4. It is seen that the datum points fall along a horizontal line at approximately 40-percent word articulation. With the average power of the interference in the pass band held constant, 0.4-microsecond pulses had approximately the same effect upon intelligibility as did 500-microsecond square waves. Statistical analysis confirms the conclusion based on inspection: pulse duration was not a significant variable. There is reason to believe that, if the noise limiter had been used, the same conclusion could have been drawn for pulse durations at least up to 100 microseconds.

The spectral distribution of the energy in a train of regularly spaced, rectangular pulses is characterized by maxima and null points, the latter occurring at multiples of the reciprocal of the pulse duration. When the pulse duration is varied, the whole pattern of maxima and null points in the interference spectrum shifts along the frequency scale. If the pulse duration is such that a *null point* falls within the pass band of the receiver, only a very small part of the total interference power (that within the pass band of the receiver on either side of the null point) is converted into audio noise. If the pulse duration is such that a *maximum* falls within the pass band of the receiver, a much larger fraction of the total interference power passes through the resonant circuits. The question therefore arises: if allowance is made for the difference in intensity, is the part of the interference spectrum near a null point equal in interference value to the part near a maximum? The over-all intensity of the interference is adjusted by means of an attenuator to make the intensity within the pass band the same in the region of the null point as in the region of the maximum. The question is whether, after such adjustment, the effects upon intelligibility are equivalent.

Again with two talkers and listening-crew W, articulation tests were conducted with the limiter inoperative, with the receiver tuned to 2.1 megacycles, and with pulse durations of 0.75, 0.95, and 1.15 microsecond. With 0.95-microsecond pulses, the pass band of the receiver spanned a null point. With 0.75- and 1.15-microsecond pulses, the receiver was tuned near maxima in the interference spectrum. The average articulation scores for the three pulse durations were: 0.75 microsecond, 27 percent; 0.95 microsecond, 28 percent; and 1.15 microsecond, 29 percent. The differences are clearly insignificant.

Thus the conclusion would appear to be justified that, if the ratio of the carrier power to the interference power within the pass band is held constant, variation in the duration of the interference pulses produces no marked effect upon intelligibility. An exception to this rule probably occurs when a noise limiter is used and when the duration of the input pulses is of the same order as that of the output pulses.

PULSE REPETITION FREQUENCY

If interference pulses occur at a repetition frequency of 10 per second or lower, they may be annoying, but they do not impair to any marked degree the intelligibility of speech heard over a

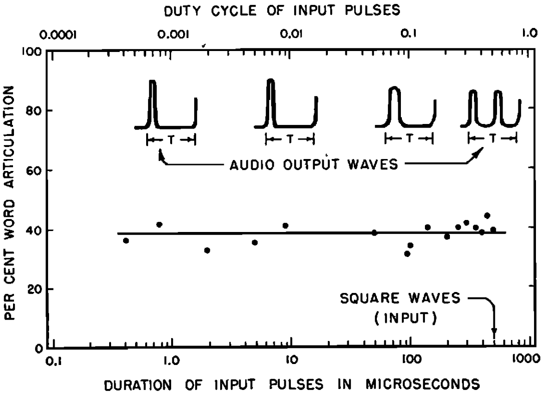

FIG. 4. Showing that intelligibility remains essentially constant despite wide variation in the duration of the input pulses. The interference consisted of rectangular pulses occurring in regular succession at a repetition frequency of 1000 per second. The carrier-to-interference ratio was held at 0 decibel by decreasing pulse amplitude to compensate for increasing pulse duration. Audio output waves corresponding to input pulse durations of 1.0, 10, 100, and 500 microseconds are shown as insets. The period T is 1 millisecond. Two talkers; listening-crew W.

properly designed receiver. Before the low p.r.f. pulses can reach an amplitude at which they might mask speech, they are limited by overload in some part of the communication circuit. If great care were taken to make the amplifying stages linear over a wide enough range to pass such pulses without amplitude limiting, the overload would occur in the listener's ears. The listener's reports of tickle, pressure, and pain discourage the use of his ears as amplitude limiters, of course; but the fact remains that moderately strong speech cannot be made unintelligible by short pulses at low p.r.f. no matter how intense the pulses.

If, on the other hand, the interference pulses occur at very high p.r.f., at a p.r.f. numerically of the same order as the band width of the receiver in cycles per second, and if they occur in a regular train, their effect is for all practical purposes indeterminate. When the p.r.f. is very high, the harmonics of the interference are widely spaced, and it may happen that all of them fall outside the pass band of the receiver. If just one of the harmonics happens to fall within the pass band, the difference between its frequency and that of the carrier is very important. Marked interference occurs if the separation is between 500 and 1000 cycles per second; very little interference is noted if the separation is greater than 2000.[5] If the harmonic should coincide with the carrier, either addition or cancellation might occur, depending upon the phase relation between the carrier and the interference. Thus the interference value of regular pulses at high p.r.f. depends upon the relation between the carrier frequency and the frequencies of certain

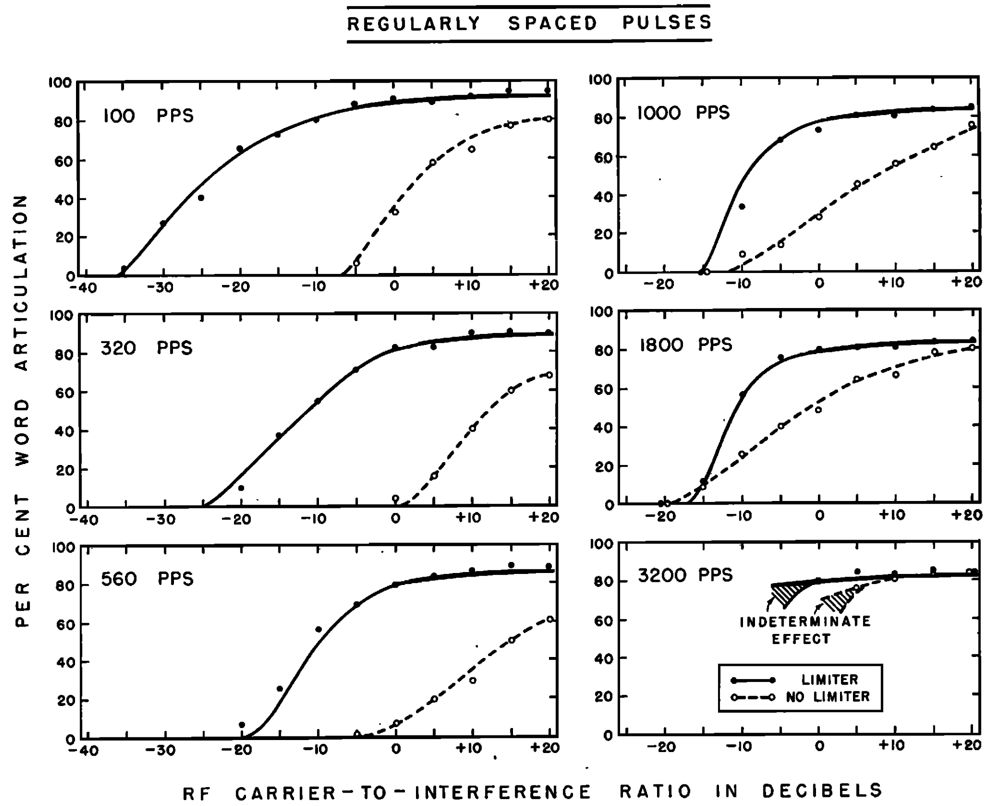

FIG. 5. Effects of *regular* impulsive interference at various pulse repetition frequencies. The curves show how intelligibility increases with increasing carrier-to-interference ratio. With p.r.f.'s below 560, the noise limiter was very effective; it provided usable reception (50-percent word articulation) with a carrier about 25 decibels weaker than that required without the limiter. With higher p.r.f.'s, the limiter was less effective. Two talkers; listening-crew W.

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[5] J. C. R. Licklider and S. J. Goffard, *The Performance of Counter-modulation and Static-cancelling Circuits in Aircraft Radio Receiver AN/ARR-15*, Harvard Psycho-Acoustic Laboratory Report PNR-9, March 1946.

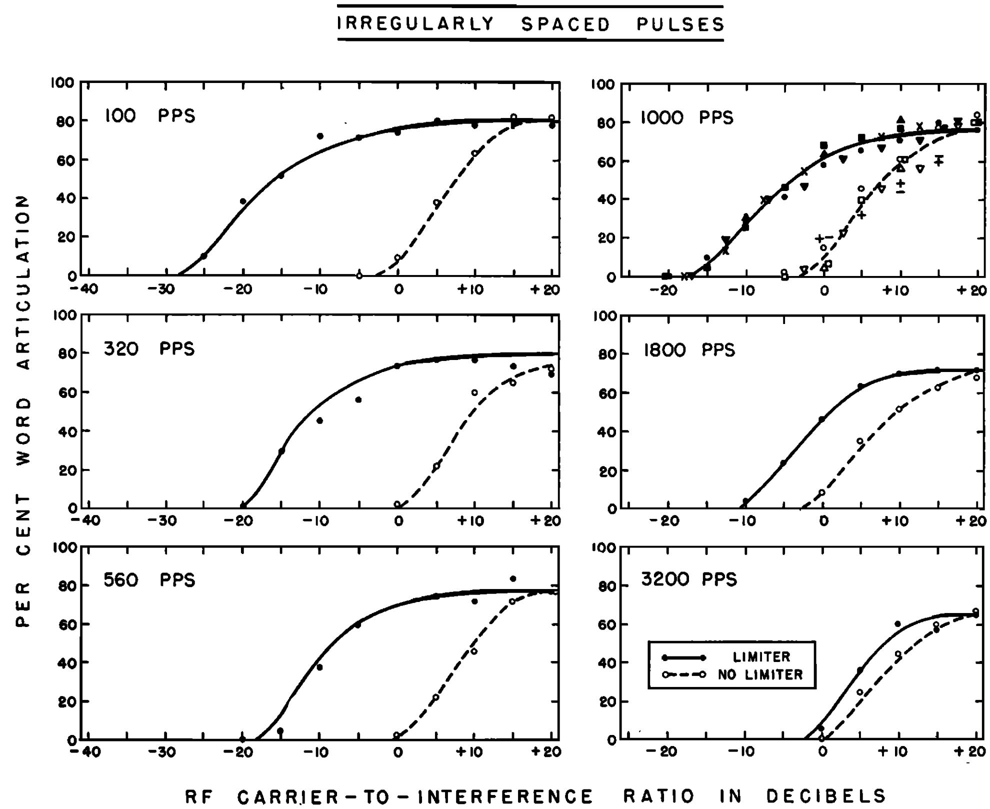

FIG. 6. Effects of *irregular* impulsive interference at various repetition frequencies. The curves appear at first glance to be roughly similar to those for regular interference (cf. Fig. 5), but more careful comparison reveals several differences: On the whole, the irregular pulses have slightly higher interference value than the regular pulses. At high p.r.f., irregular pulses become almost as interfering as fluctuation noise, whereas the effect of regular pulses becomes indeterminate. The slope of the "no limiter" curve for irregular pulses is approximately constant, whereas the slope of the corresponding curve for regular pulses varies as a function of p.r.f. One talker; listening-crew M.

harmonics of the interference. And, in the event of coincidence between the carrier and one of the harmonics, the interference value depends upon relative phase.

In between the very low and the very high p.r.f.'s, there is a range which can be studied with the aid of articulation tests. For a receiver with a 10-kilocycle pass band, this range extends approximately from 100 to 3200 pulses per second. Articulation tests were conducted, therefore, with p.r.f.'s of 100, 320, 560, 1000, 1800, and 3200, and with a wide range of carrier-to-interference ratios at each p.r.f. The source of the interference was the Colonial Pulse Generator, set for 1.15-microsecond pulse duration. The test receiver was tuned to 2.1 megacycles. The results are shown in Fig. 5.

In Fig. 5, there are two curves for each p.r.f., a solid curve to show the relation between intelligibility and carrier-to-interference ratio in tests with the noise limiter in operation, a dashed curve to show the relation in tests with the limiter disconnected. The noise limiter was highly effective against low p.r.f. interference and less effective against high p.r.f. interference. A similar relation between the effectiveness of amplitude limiting and the p.r.f. of the interference has been noted in tests of radio range receivers.[6] On the whole, the limiter provided a marked improvement in performance. It is clear that the relation between intelligibility and carrier-to-interference ratio depends to a pronounced degree upon the linearity of the receiver circuits, and that the more linear circuit was by no means the better for reception in the presence of severe impulse noise.

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[6] S. J. Goffard and J. C. R. Licklider, *Effects of Static on Radio Range Performance*, Harvard Psycho-Acoustic Laboratory Report PNR-10, March 1946.

In the tests with the limiter disconnected, an attempt was made to avoid overloading any of the receiver circuits. The dissimilarities among the dashed curves in Fig. 5 are interpreted, therefore, as showing that even with a linear receiver the interference value of impulse noise depends upon its p.r.f. The most deleterious p.r.f. is in the neighborhood of 500 pulses per second.

IRREGULARITY OF PULSES

Irregular impulse interference is encountered even more frequently than regular impulse interference. Much of the interference subsumed under the term *atmospherics* is impulsive, and irregularity is one of its most characteristic features. Irregular radio interference is often not completely random. Sometimes the deviation from complete randomness is in the direction of clustering, as in "bursts" and "grinders." Sometimes it is in the direction of uniform spacing, as when aircraft precipitation static takes on a tonal quality. For this reason, "irregular" is more accurately descriptive than is "random."

The interference used in the tests to be described was generated with the aid of an ionization-noise generator and a spark coil and gap.[7] Very sharp electrical pulses were produced whenever the ionization-noise voltage exceeded the breakdown voltage of the spark gap. Because the spectrum of the ionization noise was limited to the frequency range below 10,000 cycles per second, and because of ionization effects in the spark gap, the sequence of the pulses cannot be said to be completely random. Actually, the irregularity appeared to be quite similar to that of thunderstorm static.

Articulation tests were conducted to determine the effect of this irregularity upon the interference value of the pulses. The p.r.f.'s and the carrier-to-interference ratios were the same as those used in the tests with regular pulses. Unfortunately, the talkers and listeners employed in the previous tests were not available; a different talker and a different listening-crew (M) were used.

The results of the tests are shown in Fig. 6. Comparison of Fig. 6 with Fig. 5 indicates that, in the presence of irregular pulses as in the presence of regular pulses, the effectiveness of the limiter declines with increasing p.r.f. With the limiter disconnected, there is considerably less variation of performance with changes in p.r.f. On the whole, the articulation scores are somewhat, though not markedly, lower in the tests with irregular pulses than in the tests with regular pulses.

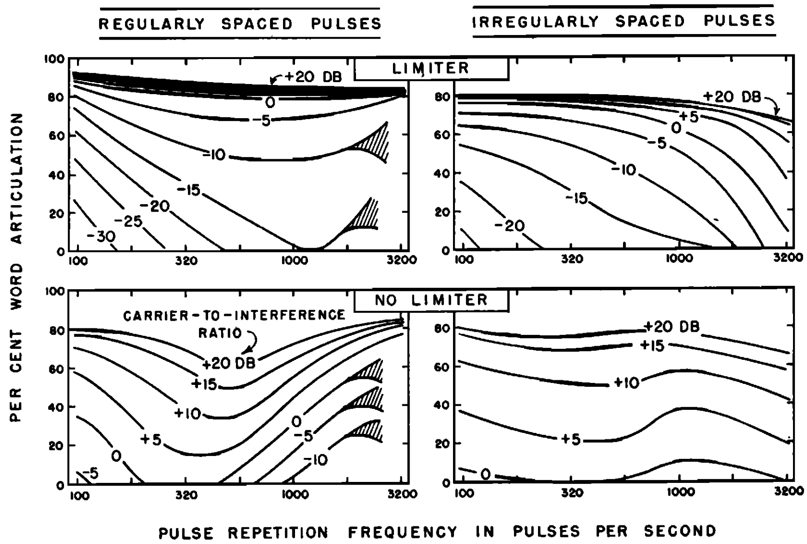

FIG. 7. Showing the relations between intelligibility and p.r.f. for regular and for irregular pulses. The upper graphs are based on the tests with the noise limiter in operation, the lower graphs on tests with the noise limiter disconnected. These curves are derived from those of Figs. 5 and 6.

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[7] J. C. R. Licklider and E. B. Newman, "Static for laboratory tests of radio receivers," Electronics 98 (June 1947).

In view of the fact that random audio pulses mask speech much more severely than do regular audio pulses, it is at first thought surprising that the curves of Figs. 5 and 6 are as similar as they are. Stevens, Miller, and Truscott[8] found that under certain conditions randomized audio pulses were as much as 50 decibels more effective than regular audio pulses in masking speech. No such difference as this appeared in the tests with radio interference.

The difference between the audio and the radio results is probably to be explained in terms of the fact that, whereas aural masking was the only factor reducing intelligibility in the audio tests, an additional factor operates in the radio situation. This additional factor, intermodulation in the detector circuits of the receiver, distorts the speech and introduces frequency components which would not appear if the speech and noise were detected separately. Reception over a radio link operating in the presence of electrical interference thus tends to be poor for two reasons: (1) in the receiver, intermodulation between the signal and the interference distorts the speech, (2) in the ear, noise and distortion products mask what is left of the speech. The intermodulation appears to cause at least as much impairment of intelligibility when the interference is regular as it does when the interference is irregular, and in the presence of regular interference it is a more important factor than aural masking. It follows, therefore, that, if audio listening tests and radio listening tests were conducted at the same speech-to-noise ratio (allowance being made for the degree of modulation in specifying the ratio in the radio tests), the audio tests should yield the higher articulation scores, and the difference between the audio scores and the radio scores should be greater in the presence of regular interference than in the presence of irregular interference.

In the upper right-hand graph of Fig. 6 are shown datum points from a number of experiments with irregular pulses at a p.r.f. of 1000. The circles (filled and unfilled) represent the scores of crew M. The squares represent the scores of crew W. The other datum points were obtained with other receivers and with other personnel. This empirical evidence of the repeatability of the results is probably of greater practical value than an estimate based on the internal consistency of a single set of experiments. As a rough rule, it appears reasonable to regard a consistent horizontal displacement of 3 decibels, or a consistent vertical displacement of 15 articulation points as due to a significant variable in the experiment.

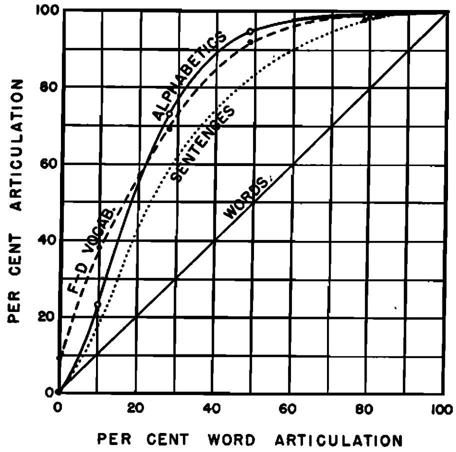

FIG. 8. Curves showing that meaningful sentences and special vocabularies are more intelligible than the monosyllabic words of the test lists. These curves are useful in predicting performance from Fig. 7.

According to this criterion, the p.r.f. of the interference is clearly a significant variable if the receiver is equipped with an amplitude limiter, no matter whether the interference is regular or irregular. Without a limiter, p.r.f. is a significant variable if the interference is regular, but it is relatively insignificant if the interference is irregular. These relations between intelligibility and p.r.f. are shown graphically in Fig. 7, in which the curves of Figs. 5 and 6 are replotted with carrier-to-interference ratio as a parameter. It is probable that the curves of the lower right-hand graph would have been horizontal straight lines if the interference had been entirely random.

DISCUSSION OF RESULTS

The results of the articulation tests provide a basis for estimating the performance to be expected from a conventional amplitude-modulation system operating against specified impulsive interference. If the performance is to be judged in terms of the intelligibility of speech material more meaningful than isolated test words, Fig. 8 is of interest. It shows how the intelligibility of sentences and of special vocabularies compares with that of the test words, i.e., of monosyllabic words heard out of context. The data for the alphabetic equivalents ("Able" for A, "Baker" for B, "Charlie" for C, etc.) and for the Fighter-Director Vocabulary (used to direct fighter planes via VHF radio from aircraft carriers) were obtained with the laboratory radio system. The curve for sentences is an estimate based on tests with audio circuits.[9,10]

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[8] S. S. Stevens, J. Miller, and I. Truscott, J. Acous. Soc. Am. 18, 418 (1946).

When heard under identical conditions, the alphabetic equivalents and the Fighter-Director Vocabulary are much more easily understood than are the discrete words used in the articulation tests. Sentences are also more easily understood than the test words because the listener can frequently "fill in" from the context. Thus, although 50-percent word articulation is usually taken as the lower limit of usable communication, it is clear that some information can be conveyed over a communication system functioning at a level of 25- or 30-percent word articulation.

The left-hand curves of Fig. 5 indicate that, with the help of a simple noise limiter, a conventional amplitude-modulation system can, under certain conditions, provide usable communication with a carrier-to-interference ratio as low as *minus* 20 decibels. Even without a noise limiter, 50-percent word articulation was obtained in most of the tests with carrier-to-noise ratios between 0 and 12 decibels. These figures stand in marked contrast to the values of 30 decibels,[11,12] 40 decibels,[13] and more,[14] cited as defining the minimum tolerable ratio of carrier to noise in broadcast reception. But broadcast reception can by no means be evaluated simply in terms of intelligibility.

It is of greater interest to compare the results of the present tests with criteria of performance which have been used in commercial and in military communication. In most instances, intensity has been the only characteristic of the interference taken into account. Various methods of measurement and various values of minimum tolerable carrier-to-interference ratio have been adopted. Little consideration has been given to p.r.f. or to the degree of regularity of the interference.

The most thorough treatment of the problem appears to have been made in connection with ship-shore and overseas radio. Even this treatment, however, fails to take into account specific non-intensitive characteristics of the interference. Actually, two different functions relating intelligibility and carrier-to-interference ratio have been used, one as the basis for ratings of "circuit merit",[15] and the other to establish the requirements for emergency communication on the Great Lakes.[16] Ratings of "circuit merit" are made in accordance with the following table:

Circuit merit (1)	Percent speech intelligibility (2)	Performance (3)	Carrier-to-interference ratio (4)
1	0–20	Hopeless	Below 8 db
2	20–40	Poor (uncommercial)	8 to 16 db
3	40–60	Fair (commercial)	12 to 22 db
4	60–80	Good (commercial)	20 to 32 db
5	80–100	Excellent (commercial)	Above 30 db

The relation between intelligibility and carrier-to-interference ratio given in the table agrees fairly closely with that shown in Fig. 3, in which the interference was fluctuation noise. The results shown in Figs. 5–7 would suggest, however, that the relation between intelligibility and carrier-to-interference ratio is more highly dependent upon non-intensitive characteristics of the interference than the ranges in the table indicate.

The results of the tests conducted on the Great Lakes indicated that 84-percent sentence

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[9] H. Pender and K. McIlwain, *Electrical Engineers' Handbook* (John Wiley and Sons, Inc., New York, 1936), Vol. V, Chap. 9, 26.

[10] S. S. Stevens, J. Miller, J. P. Egan, T. H. Waterman, and S. C. Rome, *Articulation Testing Methods*, OSRD Report No. 383, PB 22916, February 1942. Available through the Office of Technical Services, U. S. Department of Commerce, Washington, D. C.

[11] C. V. Aggers, D. E. Foster, and C. S. Young, Elec. Eng. **59**, 178 (1940).

[12] M. G. Crosby, RCA Rev. **4**, 349 (1940).

[13] Committee of the British Institution of Electrical Engineers, J. Inst. Elec. Eng. **79**, 206 (1936).

[14] R. Brown, J. Inst. Elec. Eng. **83**, 395 (1938).

[15] D. Talley, Q.S.T. **30**, 62 (1947).

[16] Federal Communications Commission. A Report of the Marine Section, Safety and Special Services Division, on the Great Lakes Engineering Study of 1941, Washington, May 1942.

intelligibility, which in Fig. 8 corresponds to 50-percent word articulation, was possible with a ratio of carrier to interference of 21 decibels, the interference (atmospherics) being measured in a 1-kilocycle band. For a 10-kilocycle band of interference, the corresponding carrier-to-noise ratio is 11 decibels. This value is very close to the values indicated by the curves of Figs. 3 and 6 which show the relation between word articulation and carrier-to-interference ratio in the tests with the noise limiter inoperative.

The present data emphasize that the amplitude-handling characteristics of the receiver must be taken into consideration if estimates of performance are to be of any value at all. This is not simply a matter of noting whether or not the receiver is equipped with a noise limiter, because all limiters are not equally effective, and because, even without noise limiters, good operators frequently obtain limiting in intermediate-frequency or in audiofrequency circuits by overdriving their receivers. As a rough rule, amplitude limiting can be disregarded in predicting performance if the p.r.f. of the interference (in pulses per second) is one-third as high as the IF band width of the receiver (in cycles per second). If the p.r.f. is low, however, the amplitude-limiting characteristic of the receiver is probably the most important factor governing performance. This discussion assumes that if circuits such as automatic volume controls and squelches are used, they are free from special vulnerabilities which would impair performance in the presence of impulsive interference.

CONCLUSIONS

The results of word articulation tests, conducted in the laboratory with an amplitude-modulation radio system operating in the presence of electrical interference, lead to the following conclusions:

(1) The characteristics of impulsive interference which determine its interference value include intensity, pulse repetition frequency, and degree of regularity. On the whole, the duration of the pulses and the shape of the interference spectrum are not major factors except insofar as they affect the intensity of the interference within the pass band of the receiver.

(2) Usable communication—50-percent intelligibility in tests with unrelated monosyllabic words—was obtained with carrier-to-interference ratios ranging from *minus* 20 decibels to *plus* 15 decibels, depending upon the type of interference and the amplitude-handling characteristics of the receiver. Thus performance cannot be predicted accurately on the basis of carrier-to-interference ratio alone.

(3) The relation between pulse repetition frequency and interference value depends upon whether or not amplitude limiting occurs in the receiver. When there is no amplitude limiting, the most detrimental pulse repetition frequency is in the neighborhood of 500 pulses per second. When a limiter is used, interference value increases with increasing p.r.f.

(4) Radiofrequency interference consisting of pulses in regular sequence gives rise to a periodic audio wave which sounds like a musical tone. If the number and the shape of the pulses which constitute the radiofrequency interference are held constant, but their times of occurrence are randomized, the audio wave loses its tonal quality. The irregularly-spaced pulses sound like "static" or like "white" noise, depending upon the repetition frequency. Irregular interference is on the whole more detrimental than regular interference.

(5) With the aid of the curves of Fig. 7, it is possible to predict the performance of a conventional amplitude-modulation radio system if the band width is approximately 10 kilocycles and if the important characteristics of the interference are specified.